EFFECT OF THINNING ON PARTITIONING OF ABOVEGROUND BIOMASS IN NATURALLY REGENERATED SHORTLEAF PINE (*PINUS ECHINATA* MILL.)

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INTRODUCTION

Shortleaf pine (*Pinus echinata* Mill.) is one of the important pine species in the southern United States. It is the focus of ecological restoration efforts in the Ozarks of Missouri and the Ouachita mountain region of Arkansas and southeast Oklahoma. However, the species has not been the subject of research to as great an extent as the other major southern pine species so that it has sometimes been referred to as the forgotten species among southern pines. Therefore, forest managers in areas where shortleaf pine forms a significant portion of the species composition have at times been faced with shortage of information on which to base certain management decisions. The ability to accurately estimate tree and tree component biomass and how its partitioning in stands is affected by various silvicultural treatments is important particularly in the current times when carbon sequestration is becoming appreciated as an important environmental role of forests.

This study examined the effect of thinning, a silvicultural treatment done to give residual trees more growing space, on the partitioning of biomass among branches, foliage, bark and bole wood in shortleaf pine trees. Two manuscripts have been prepared from this study and will be submitted separately for publication to the Southern Journal of Applied Forestry. The first, referred to as Manuscript I, "Tree biomass equations for naturally regenerated shortleaf pine in southeast Oklahoma," reports the fitting of biomass equations for shortleaf pine using data from the study and identifies the best biomass equations that can be used to estimate tree and tree component biomass equations in naturally regenerated shortleaf pine. This is important as there are no recently developed tree biomass equations for shortleaf pine that can be used in biomass related studies. The biomass equations reported in Manuscript I are used in the estimation of tree component biomass to provide data needed for the biomass partitioning study that is reported in the second manuscript. The second manuscript is referred to as Manuscript II in this thesis. The biomass equations reported in Manuscript I can also be used in other biomass related studies of shortleaf pine. They are also useful for forest managers who need biomass estimates for making management decisions.

CHAPTER II

MANUSCRIPT I

TREE BIOMASS EQUATIONS FOR NATURALLY REGENERATED SHORTLEAF PINE (*PINUS EHINATA* MILL.) IN SOUTHEAST OKLAHOMA

Abstract

Aboveground tree and tree component biomass equations were fitted, by nonlinear seemingly unrelated regression, for even-aged naturally regenerated shortleaf pine in southeast Oklahoma; using data from 46- to 53-year-old stands growing in stand densities ranging from thinned to 50 percent of full stocking to overstocked unthinned stands. Stand density was found to have an effect resulting in different estimates of some parameters for trees growing in thinned vs. unthinned stands. Equations based on diameter at breast height (dbh) alone gave biomass estimates that were not significantly different from those obtained with equations based on dbh, height and/or crown width. The fitted component equations were additive. The equations can be used to estimate aboveground tree or tree component biomass for naturally regenerated shortleaf pine in the dbh range 7 to 40 cm in the southeast Oklahoma and have the potential for application in other shortleaf pine growing areas.

Introduction

Tree biomass equations provide estimates of tree and tree component biomass based on tree dendrometric measurements. The estimates are useful as they provide information on forest carbon stocks, fuel quantity in forest stands for fire management and for wood fuel production purposes, and the amount of wood fiber available for pulp mills and other similar users. They are also useful to ecologists studying productivity of forest ecosystems and to tree physiologists studying carbon production and allocation among tree components. With increased concerns of global warming and climate change, there is increased need for reliable tree biomass equations to help quantify the role of forests in mitigating the climate change and to help governments assess their progress towards meeting global policy commitments such as the Kyoto Protocol. According to Schoene (2002), countries may fulfill their individual commitment to the Kyoto Protocol by reducing emissions from sources or by recapturing carbon dioxide in sinks such as forests and soils. Tree biomass equations are needed to quantify carbon dioxide recaptured in forests; especially for regionally important species such as shortleaf pine.

Shortleaf pine (*Pinus echinata* Mill.) forms a significant proportion of tree species in the southern United States. According to Smith et al. (2001), loblolly-shortleaf pine forests cover 50 million acres or nearly one-fourth of all southern forests and account for over one-half of 95 million acre softwood forests in the eastern United States. Shortleaf pine accounts for one quarter of total southern pine volume (Schulte and Buongiorna 2004). McWilliams et al. (1986) reported that shortleaf pine is distributed more widely than any other southern pine and is the principal softwood species in Ouachita and Ozark mountains of Arkansas, Missouri, and Oklahoma. Shortleaf pine is the species of focus in the ecological restoration projects in the Ozarks of Missouri and Ouachita mountain region of Arkansas and Missouri. Hamilton (2003) attributed the interest in its management to the dramatic decrease in acreage of the species since Euro-American settlement. In addition, Ozark region health issues of red oak borer and oak decline have underlined the importance of maintaining a conifer component (Stambaugh and Guyette 2004). Reliable tree biomass equations for shortleaf pine are therefore needed in the southern United States in general and the Ouachita and Ozark region in particular, to help forest managers quantify the benefits from shortleaf pine management efforts and make accurate management decisions.

Tree Biomass Equations

Tree biomass equations are commonly developed by regression analysis methods. A tree dendrometric variable that is easier to measure is related to biomass by a function whose parameters are fitted by regression analysis. According to Parresol (1999), biomass equations have been developed utilizing one of the following three forms:

Linear (additive error): $Y = \beta_0 + \beta_1 X_1 + ... + \beta_j X_j + \varepsilon$ (1)

Nonlinear (additive error): $Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} ... X_j^{\beta_j} + \varepsilon$ (2)

Nonlinear (multiplicative error): $Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} ... X_j^{\beta_j} \varepsilon$ (3)

where Y = total or component biomass, X_j = tree dimension variable, β_j = model parameter, and ε = error term; with diameter at breast height (D), D^2, total height (H), D^2H, age, and live crown length (LCL) being some of the commonly used tree dimension variables.

Most reported tree biomass equations (e.g. Loomis et al. 1966; Ter-Mikaelian and Korzukhin 1997; Lambert et al. 2005) have utilized model form (3). This preference may be attributed to the fact that error variance in tree biomass measurements exhibits heteroscedasticity, which is easily accommodated when model (3) is log transformed and the parameters fitted by linear regression. Also, the relationship between biomass and tree dendrometric variables is often a power function, as implied by allometric theory (Huxley 1924, 1932) hence model form (3) tends to fit well to biomass data.

Other reported model forms include:

$$F_B = \xi dob^{\beta} C_h^{\tau} \left[2(1 - e^{-\gamma l}) - \gamma l(\gamma l + 2)e^{-\gamma l} \right] \qquad (4)$$

where,

F_B is foliage biomass

dob is diameter outside bark at the base of the live crown

C_h is crown height

l is live crown length

ξ, β, τ, γ are parameters

and

$$\ln(m) = \alpha * [d/(d + \beta)] + \gamma * h + \delta * \ln(h) + \varsigma * \ln(l_c) + \varepsilon \qquad (5)$$

where

m is dry mass of the component (kg)

$\alpha, \beta, \gamma, \delta, \zeta$ are parameters

ε is the random error term

d is diameter at breast height (cm)

h is tree height (m)

l_c is length of the living crown (m)

Model (4) was developed by Zhang et al. (2004) for prediction of foliage biomass. They argued that this model is a mechanically reasonable model based on the relationship between foliage biomass and crown characteristics subject to logical constraints such as foliage biomass should be zero if crown length is zero. They found this model to produce reliable predictions of foliage biomass for stands managed under a wide array of silvicultural treatments in Georgia, US. Model (5), known as Marklund's (1988) model, was found by Kärkkäinen (2005) to provide acceptable estimates for biomass of different components of trees over the whole diameter range, regardless of species, in Finland.

Existing biomass model forms, therefore, vary in complexity with regards to functional forms of the predictor variables and the number of parameters. Simple model forms e.g. those utilizing only dbh as a predictor have an advantage of having low data requirements and can be fitted easily by computing software without parameter convergence issues. More complex model forms, on the other hand, require more data and often lead to parameter convergence issues due to the large number of parameters to be fitted and intricate functional forms. Models forms utilizing predictor variables readily available from forest inventory data are the most appropriate as their application would rarely be hampered by data availability problems. Such models are desirable for day to day management decision making by foresters. More complex models, if successfully fitted, may be more suitable for use by researchers who wish to examine theoretical properties of these models.

Biomass equations for shortleaf pine have been fitted by Loomis et al. (1966), Clark III and Taras (1976), Saucier et al. (1981), Phillips and McNab (1982), and Clark III and Saucier (1990). The study by Loomis et al. (1966) focused on the branches and foliage while that by Clark III and Saucier (1990) focused on total tree biomass and bole biomass to certain merchantable heights. Saucier et al. (1981) developed green weight and volume tables for the major southern pine species including shortleaf pine. Their tables provide green weights for total trees including wood, bark and foliage as well as volumes and weights for tree stems to a variety of top limits. Phillips and McNab (1982) focused on green weight of sapling-sized trees ranging in dbh from 1.0 to 4.9 inches (2.54 to 12.4 cm). The study by Clark III and Taras (1976) focused on dry weights of all aboveground tree components, but utilized linear regression techniques to fit equations to the log transformed form of model (6)

$$Y = \beta_0 (D^2 H)^{\beta_1} \varepsilon \qquad (6)$$

where Y = tree component biomass, D = dbh, H = tree total height, β_0 and β_1 = parameters and ε = random error term.

Objective of the Study

The objective of this study was to fit biomass equations for shortleaf pine using model forms (3), (4), and (5) then select the best model form based on fit index (FI), model root mean square error (RMSE), constancy of error variance across tree size, and additivity of component biomass equations. The current study is an improvement over previous studies because it focused on dry weight of all aboveground tree components and fitted the equations by nonlinear regression methods. It also incorporated crown variables for branch and foliage biomass. The results will therefore be more accurate in estimating tree and tree component biomass for shortleaf pine.

Methods

Study Area

Data for the study were obtained from research plots established in 1990 to study the effect of thinning on growth and yield of even-aged naturally regenerated shortleaf pine (Wittwer et al. 1998). The plots were located in shortleaf pine stands in Ouachita Mountains of Pushmataha County, Oklahoma (approximately 34°20'N latitude and 95°00' W longitude). The land was owned by Plum Creek Timber Company. There were eight circular plots each about 0.08 ha in area and one plot of about 0.04 ha in area. Each plot was surrounded by a 10.1 meter buffer strip. Three plots had been thinned to 50 percent of full stocking (identified as 50FS), three to 70 percent of full stocking (identified as 70FS), and three served as unthinned controls. The unthinned controls had a stocking of over 120 percent of full stocking hence also identified as > 120FS. The stocking percentages are according to the shortleaf pine stocking guide developed by Rogers (1983). According to Wittwer et al. (1998), the stands were 30 to 37 years old in 1990 and growing on a site of site index, at base age 50, of 22.25 meters. The site index estimates were obtained by using the polymorphic site index curves of Graney and Burkhart (1973). The stands had an initial basal area of $44 m^2 ha^{-1}$. The stand conditions immediately after thinning and the conditions when data for the current study were collected are shown in Table 1 and Table 2 respectively. According to Bain and Watterson (1979), the soil of the area is mapped in the Sherwood (Fine-loamy, mixed, semiactive, thermic Typic Hapludults) - Zafra (Loamy-skeletal, siliceous, semiactive, thermic Typic Hapludults) association.

Table 1. Average stand conditions immediately after thinning in 1990

Treatment	Trees/ha	Dbh[1] (cm)	BA[2] (m^2/ha)	Height[3](m)
50 FS	567	19.0	16.0	16.4
70 FS	850	18.3	22.3	16.6
CONTROL (>120FS)	2287	15.1	40.5	17.0

[1] Quadratic mean dbh

[2] Basal area

3 Average height of dominants and codominants

Table 2. Average stand conditions when data for the current study were collected in 2006

Treatment	Stocking[1]	Trees/ha	Dbh[2] (cm)	BA[3] (m^2/ha)	Height[4](m)
50 FS	90	562	27.6	33.7	22.7
70 FS	115	825	24.9	40.3	23.2
CONTROL (>120FS)	>120	1452	21.0	49.7	23.6

[1]Stocking as a percentage of full stocking

[2] Quadratic mean dbh

[3] Basal area

[4]Average height of dominants and codominants

Data Collection

In January and February of 2006, four trees, sampled to cover the extent of the range of diameter classes in the study plot, were felled in each of the plots. The thirty-six sampled trees were representative of the extent of the diameter class range 7 to 40 cm. Each of the sampled trees was sub-sampled for tree component biomass estimation. Data on dbh, total tree height, height to live crown, and crown width, for the sampled trees, were obtained from the measurements for each of the study plots that were conducted during the dormant season following the 2005 growing season.

Estimating Bole Wood and Bole Bark Biomass

The sampled trees were felled at an about 0.14 m above the ground. The bole of each sampled tree was cut into log lengths up to the point of 1 centimeter top diameter. The first log length was about 1.23 m long as this was log between the stump and the tree's breast height. Logs above breast height were each 2.13 m long. Any part of the bole less than 1 cm top diameter was considered to be the terminal branch. The cutting of the log lengths could stop at a point greater than 1 cm top diameter if the last section was less than 2.13 meters in length. Each log length was weighed and its green weight recorded. A disc about 3 cm thick was cut from the upper end of each log length and from the stump. The discs made up the sub-samples from the tree bole. The inside bark and outside bark diameters for each of the discs were determined using calipers to provide information on the top and bottom diameters for each of the log lengths. Each disc was weighed with and without the bark to determine the green weight of the disc with bark and disc without bark. The debarked discs and bark samples from each disk were dried, in an oven at 60°C to constant weight and their dry weight determined. For each disc, dry weight with bark and dry weight without bark were then computed.

Dry weight – Green weight ratios were computed for each disc; with bark and without bark. The ratios were then used with equation (7) to estimate the dry weight of the wood and of the bark on each 2.13 meter bole length.

$$DW_{WB} = GW * \left(\frac{R_1 D_{1ob}^{\ 2} + R_2 D_{2ob}^{\ 2}}{D_{1ob}^{\ 2} + D_{2ob}^{\ 2}} \right) \tag{7}$$

where

DW_{WB} is the dry weight of the 2.13-meter bole length with bark in kilograms

GW is the green weight of the 2.13-meter bole length with bark in kilograms

R_1 is the dry weight-green weight ratio of the disc on the lower end of the 2.13-meter bole length

R_2 is the dry weight-green weight ratio of the disc on the upper end of the 2.13-meter bole length

D_{1ob} is the geometric mean diameter, outside bark, of the disc on the lower end of the 2.13-meter bole length in centimeters

D_{2ob} is the geometric mean diameter, outside bark, of the disc on the upper end of the 2.13-meter bole length in centimeters

Equation (7) weights each dry weight-green weight ratio with the cross sectional area of the disc. It gives a weighted average density using discs at the top and bottom of each bole section. Disc dry weight-green weight ratio varied between 0.4 and 0.7 and there did not appear to be a trend in the dry weight-green weight ratio with tree height. For dry without bark-DW_{WO}, of each of the log lengths, equation (7) was used but with inside bark diameters in place of the outside bark diameters, and disc ratios of dry weight inside bark to green weight outside bark instead of those indicated above.

Tree bole wood biomass was obtained by summing up the dry weights, without bark, for the 2.13-meter bole lengths in the tree. Tree bole bark biomass was obtained by summing up the dry weights, with bark, for the 2.13-meter bole lengths the subtracting the total tree bole wood biomass from it. The tree bole, bole wood, and bark biomass estimates for each of the sampled trees are shown in Appendix I.

Estimating Branch and Foliage Biomass

One branch per whorl and every terminal branch were sampled for estimation of tree branch and foliage biomass. The basal diameter of the sampled branches and that of each of the other branches on the tree was determined and recorded to the nearest 0.1 centimeter. All foliage was plucked off each sampled branch and placed into paper sacks. Each sampled branch was then chopped into lengths of about 10 to 30 cm and placed into paper or burlap sacks. The branch and foliage samples were dried in an oven at 60^{o}C to constant weight. Regression equations relating branch, tree, and stand variables to branch foliage and wood (with branch bark) dry weights were then fitted to be used to estimate the dry weights of the branches that were not sampled.

Regression equations to estimate branch and branch foliage dry weights were fitted from the general equation (8) developed by Ek (1979).

$$w = \beta_0 d^{\beta_1} R^{\beta_2} S^{\beta_3} \varepsilon \qquad (8)$$

where:

w is the branch or branch foliage dry weight in grams

d is the branch basal diameter in centimeters

R is a measure of depth of branch in the crown, in meters, obtained as (H-h) where h is height to the branch and H is the total height of the tree

S is the ratio (H/D) where D is the dbh of the tree, in centimeters and H is the total height of the tree, in meters

β_0, β_1, β_2, and β_3 are parameters

ε is the error term

Equation (8) was log transformed and STEPWISE SELECTION on the log transformed predictor variables, using the REG procedure in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004), done to identify variables significant in predicting single branch dry weight. A variables was considered significant if $p \leq 0.15$ Different variables were found to be significant in the different thinning treatments and whether for branch or for branch foliage biomass.

Weighted nonlinear regression, using the NLIN procedure in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004), was then used to fit the parameters of the nonlinear model form (8) containing only the variables that had been found to be significant. The function d^{-2}, where d is the branch basal diameter, was used as the weight function for the foliage biomass equations. The functions $d^{-4.5}$, $d^{-4.5}$, and d^{-2} were used as weight functions for branch biomass equations in thinned to 50 percent, thinned to 70 percent, and unthinned treatments respectively. The equations with the best fit statistics (Table 3 and 4) were then used to estimate dry weight for each of the branches that had not been sampled. For the branches that had been sampled, the actual dry weights were used. Tree crown branch biomass and foliage biomass were found by summing the dry weight values for each of the branches on the tree. The branch (without foliage) and foliage biomass estimates for each of the sampled trees are shown in Appendix I.

Table 3 Equations for estimating dry weight for branches (without foliage) that were not sampled

Treatment	Equation	Fit Index	RMSE (grams)
50FS	$w = 17.3102d^{2.8464}$	0.8876	679.25
70FS	$w = 16.441d^{3.0065}S^{0.365}$	0.9687	247.79
CONTROL (>120FS)	$w = 17.914d^{2.815}$	0.9670	167.69

where:

w is the branch dry weight in grams

d is the branch basal diameter, in centimeters

S is the ratio (*H*/*D*) where *D* is the diameter at breast height of the tree, in centimeters and

H is the total height of the tree, in meters

Table 4 Equations for estimating dry weight of foliage on branches that were not sampled

Treatment	Equation	Fit Index	RMSE (grams)
50FS	$w = 29.9575d^{1.6886}R^{-0.3149}$	0.6354	98.09
70FS	$w = 25.4143d^{2.0003}R^{-0.4452}$	0.6220	97.96
CONTROL (>120FS)	$w = 28.6883d^{1.1231}S^{-1.1286}$	0.3746	80.08

where:

w is the dry weight of foliage on the branch in grams

d is the branch basal diameter, in centimeters

R is a measure of depth of branch in the crown, in meters, obtained as (*H*-*h*) where *h* is height to the branch and *H* is the total height of the tree

S is the ratio (*H*/*D*) where *D* is the diameter at breast height of the tree, in centimeters and *H* is the total height of the tree, in meters

The parameter estimates of the equations in Tables 3 and 4 above were significantly different from zero at 95 percent confidence level. The standard errors and the 95 percent confidence intervals of the parameter estimates are shown in Appendix III. The residual plots for these equations are shown in Appendix II.

Of the variables investigated, branch basal diameter was the common predictor variable for both branch and foliage biomass under all stand conditions. The variable *R* was not significant in branch biomass equations. The depth of a branch in the crown did not influence biomass of a branch beyond the influence of the branch basal diameter. This variable was significant in the foliage biomass equations for the thinned stands. This suggests that there was significant variation in amount of foliage on a branch due to position of the branch in the crown. The variable is raised to a negative power, hence branches of the shortleaf pine trees had less foliage the deeper they were in the crown, given equal branch basal diameters.

Fitting the Tree-level Biomass Equations

Weighted nonlinear regression, using the NLIN and MODEL procedures in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004), were used to fit the parameters of model forms (3), (4), and (5) to tree-level biomass components. Equations were fitted to the data in Appendix I. The effect of stand density on the parameters was investigated by including dummy variables for stand density in the models of the form (3) and investigating their significance by the STEPWISE SELECTION method using REG procedure in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004). The dummy variables used were:

X_1 = 1 if the stand was under CONTROL treatment

= 0 otherwise

X_2 = 1 if the stand was under 70FS treatment

= otherwise

Two forms of model (3) were investigated; the form with dbh only as the predictor variable and the form with other tree dendrometric variables (tree height, live crown length, and crown width) in addition to dbh. STEPWISE SELECTION with a p = 0.15 variable inclusion criterion, on log transformed forms of the models, using the REG procedure in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004), was used to select the significant variables. Equations (9), (10), and (11) were used, with the STEPWISE SELECTION method, to investigate the significant predictors, dummy variables, and interactions between the dummy variables and the predictors.

$$\ln(Y) = \beta_0 + \beta_1 \ln(DBH) + \beta_2 X_1 + \beta_3 X_2 + \beta_4 X_1 \ln(DBH) + \beta_5 X_2 \ln(DBH) \quad (9)$$

$$\ln(Y) = \beta_0 + \beta_1 \ln(DBH) + \beta_2 \ln(H) + \beta_3 X_1 + \beta_4 X_2 + \beta_5 X_1 \ln(DBH) + \beta_6 X_2 \ln(DBH) + \beta_7 X_1 \ln(H) + \beta_8 X_2 \ln(H) \quad (10)$$

$$\ln(Y) = \beta_0 + \beta_1 \ln(DBH) + \beta_2 \ln(H) + \beta_3 \ln(CW) + \beta_4 \ln(LCL) + \beta_5 X_1 + \beta_6 X_2 + \beta_7 X_1 \ln(DBH) + \beta_8 X_2 \ln(DBH) + \beta_9 X_1 \ln(H) + \beta_{10} X_2 \ln(H) + \beta_{11} X_1 \ln(CW) + \beta_{12} X_2 \ln(CW) + \beta_{13} X_1 \ln(LCL) + \beta_{14} X_2 \ln(LCL) \quad (11)$$

where:

ln is the natural logarithm

Y is the tree or tree component biomass in kilograms

H is the total height of the tree in meters

CW is the crown width in meters

LCL is the length of the life crown in meters

X_1 and X_2 are dummy variables

β_0 is the intercept parameter

β_1 to β_{14} are slope parameters

Equation (9) was used to investigate the significance of the dummy variables in bole wood, tree bole, branch, and foliage biomass equations with only dbh as the dendrometric predictor variable. Equation (10) was used to investigate significant variables for bole wood and tree bole biomass equations that included height and dbh. Equation (11) was used to investigate the significant variables that included dbh, height as well as several crown dimension variables for tree level branch and foliage biomass equations.

The STEPWISE SELECTION on equation (9) using data for the bole wood and tree bole revealed β_0, β_1, and β_2 to be the only significant parameters. The STEPWISE SELECTION using data for branches and foliage revealed β_0, β_1, and β_4 to be the significant parameters. Using only the significant parameters, equation (9) was converted to the nonlinear forms (12) and (13).

$$Y = \exp^{(\beta_0 + \beta_2 X_1)} (DBH)^{\beta_1} \tag{12}$$

$$Y = \exp^{\beta_0} (DBH)^{[\beta_1 + \beta_4 X_1]} \tag{13}$$

where:

Y = is the tree component biomass in kilograms

β_0, β_1, β_2, and $\beta_4$are parameters

X_1 is the dummy variable with value 1 for unthinned stand and zero for thinned stands

Equation (12) was fitted for tree bole and bole wood biomass while equation (13) was fitted for tree branch and foliage biomass. The intercept parameter was fitted in the exponential function form rather than in the normal multiplicative form to restrict the confidence interval for the multiplicative intercept parameter from including zero as the value of this parameter was so small for some of the tree components that the 95 percent confidence interval for the parameter estimate sometimes included zero. The parameters in equations (12) and (13) were then fitted in a system of equations (14) by weighted nonlinear seemingly unrelated regression (NSUR) using the MODEL procedure in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004).

$$
\begin{aligned}
Y_{BOLEWOOD} &= \exp^{(\beta_{11}+\beta_{12}X_1)}(DBH)^{\beta_{13}} \\
Y_{TREEBOLE} &= \exp^{(\beta_{21}+\beta_{22}X_1)}(DBH)^{\beta_{23}} \\
Y_{BRANCH} &= \exp^{\beta_{31}}(DBH)^{[\beta_{32}+\beta_{33}X_1]} \\
Y_{FOLIAGE} &= \exp^{\beta_{41}}(DBH)^{[\beta_{42}+\beta_{43}X_1]} \\
Y_{TOTALTREE} &= \exp^{(\beta_{21}+\beta_{22}X_1)}(DBH)^{\beta_{23}} + \exp^{\beta_{31}}(DBH)^{[\beta_{32}+\beta_{33}X_1]} + \exp^{\beta_{41}}(DBH)^{[\beta_{42}+\beta_{43}X_1]}
\end{aligned}
\tag{14}
$$

where:

the dependent variable in each of the equations in the system is the tree component biomass in kilograms

β_{11} to β_{43} are parameters

X_1 is a dummy variable with value 1 for unthinned stand and zero for thinned stands

According to Parresol (2001) fitting parameters of tree and tree component biomass equations as a unified system by this method results in efficient parameter estimates and ensures additivity of the tree component biomass regression equations. This results in regression functions that are mutually consistent so that predictions for the components sum to the prediction from the total tree regression, which is a desirable feature. In the system of equations (14), the parameters and the variables of the total tree biomass equation were restricted to be the same as those in the component equations. This ensured additivity of the biomass equations. The weight function used was $DBH^{-2.5}$ for the branch biomass equation and DBH^{-1} for the other equations in the system of equations (14).

Using equations (10) and (11) to investigate the significant variables and stand density interactions in equations with tree height, live crown length, and crown width in addition to dbh, it was found out that for the bole wood and the tree bole, β_0, β_1, β_2, and β_7 in equation (10) were the significant parameters. That is, the biomass of these components was significantly related to dbh and tree height with the dummy variable X_1 modifying the relationship with height in unthinned stands. For branches and foliage, the significance of the live crown length (*LCL*), the crown width, and interactions with dummy variables for stand density were investigated. The parameters β_0, β_1, and β_3, in equation (11) were the only ones found to be significant. That is, dbh and crown width were the only variables that were significantly related to branch or foliage biomass. The equations, with only the significant parameters, were converted to the nonlinear forms (15) and (16) then fitted in a system of equations (17) by weighted NSUR using the MODEL procedure in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004) as described for the system of equations (14).

$$Y_B = \exp^{\beta_0}(DBH)^{\beta_1} H^{(\beta_2+\beta_7 X_1)} \tag{15}$$

$$Y_C = \exp^{\beta_0}(DBH)^{\beta_1}(CW)^{\beta_3} \tag{16}$$

where:

Y_B is the tree bole or bole wood biomass in kilograms

Y_C is the branch or foliage biomass in kilograms

H is the height of the tree in meters

CW is the crown width of the tree in meters

β_0, β_1, β_2, β_3, and β_7 are parameters

X_1 is the dummy variable with value 1 for unthinned stand and zero for thinned stands

$$Y_{BOLEWOOD} = \exp^{\beta_{11}}(DBH)^{\beta_{12}} H^{(\beta_{13}+\beta_{14}X_1)}$$

$$Y_{TREEBOLE} = \exp^{\beta_{21}}(DBH)^{\beta_{22}} H^{(\beta_{23}+\beta_{24}X_1)}$$

$$Y_{BRANCH} = \exp^{\beta_{31}}(DBH)^{\beta_{32}}(CW)^{\beta_{33}} \tag{17}$$

$$Y_{FOLIAGE} = \exp^{\beta_{41}}(DBH)^{\beta_{42}}(CW)^{\beta_{43}}$$

$$Y_{TOTALTREE} = \exp^{\beta_{21}}(DBH)^{\beta_{22}} H^{(\beta_{23}+\beta_{24}X_1)} + \exp^{\beta_{31}}(DBH)^{\beta_{32}}(CW)^{\beta_{33}} + \exp^{\beta_{41}}(DBH)^{\beta_{42}}(CW)^{\beta_{43}}$$

where:

the dependent variable in each of the equations in the system is the tree component biomass

H is the height of the tree in meters

CW is the crown width of the tree in meters

β_{11} to β_{43} are parameters

X_1 is a dummy variable with value 1 for unthinned stand and zero for thinned stands

Equation (4) was fitted on foliage biomass data only. Modification was done to this equation to utilize dbh rather than the outside bark diameter at the base of the live crown (*dob*), and include a dummy variable that would account for the effect of stand density on model parameters. This was necessary as a measure of the *dob*, required by the model, was not available in the data set; and, the model was not designed to utilize crown width which for this study seemed an important indicator of stand density. A comparison of equations (13) and (16) suggested that the presence of the crown width variable in an equation would make a dummy variable for stand density unnecessary and its absence would make the dummy variable necessary. Crown width was therefore an important component of equation (4) for the shortleaf pine data. In its absence, a dummy variable for stand density would be needed in (4), hence the need to modify this equation to contain a dummy variable for stand density.

Equation (4) was therefore modified to equation (18) and the model parameters fitted by weighted nonlinear regression using the NLIN procedure in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004).

$$F_B = \xi DBH^{(\beta+\delta X_1)} C_h^{\tau}\left[2(1-e^{-\gamma l}) - \gamma l(\gamma l + 2)e^{-\gamma l}\right] \tag{18}$$

where:

F_B is foliage biomass in kilograms

C_h is crown height in meters

l is the live crown length in meters

ξ, β, τ, γ, δ are parameters

X_1 is a dummy variable with value 1 for unthinned stand and zero for thinned stands

The ability of the biomass estimates of this equation to add up successfully with the estimates of branch and tree bole biomass was investigated by substituting the parameters and variables of this equation in the system of equations (17) in place of those for the foliage equation. However, the parameters of the new system could not converge.

Parameters of equation (5) were not fitted due to parameter convergence issues. The parameters of this equation could not be fit using the shortleaf pine biomass data.

Results and Discussion

The parameter estimates for the equations utilizing dbh as the only tree dendrometric predictor variable, fitted in the system of equations (14), are shown in Table 5. All the parameters, except β_{22}, were significant at $p \leq 0.05$. Parameter β_{22} was dropped from the system of equations (14) and the remaining parameters re-fitted. The re-fitted parameter estimates are shown in Table 6. All the parameters in this table are significant at $p \leq 0.05$. The corresponding biomass estimates were found to be additive.

Table 5 Estimates and significance statistics for the parameters of dbh-only biomass equations fitted in the system of equations (14)

Parameter	Estimate	Standard Error	t-value	p-value
β_{11}	-1.53636	0.1666	-9.22	<0.0001
β_{12}	-0.06992	0.0295	-2.37	0.0239
β_{13}	2.158424	0.0494	43.66	<0.0001
β_{21}	-1.42403	0.1756	-8.11	<0.0001
β_{22}	-0.04398	0.0306	-1.44	0.1600
β_{23}	2.150806	0.0521	41.30	<0.0001
β_{31}	-8.65546	0.3671	-23.58	<0.0001
β_{32}	3.636283	0.1060	34.31	<0.0001
β_{33}	-0.10272	0.0268	-3.84	0.0005
β_{41}	-5.56234	0.3768	-14.76	<0.0001
β_{42}	2.213155	0.1107	19.99	<0.0001
β_{43}	-0.09365	0.0238	-3.93	0.0004

Table 6 Estimates and significance statistics for the parameters of dbh only biomass equations fitted in the system of equations (14) without parameter β_{22}

Parameter	Estimate	Standard Error	t-value	p-value
β_{11}	-1.57006	0.1680	-9.34	<0.0001
β_{12}	-0.03041	0.0114	-2.66	0.0120
β_{13}	2.16522	0.0502	43.16	<0.0001
β_{21}	-1.46237	0.1758	-8.32	<0.0001
β_{23}	2.158555	0.0525	41.11	<0.0001
β_{31}	-8.6521	0.3653	-23.68	<0.0001
β_{32}	3.633177	0.1054	34.46	<0.0001
β_{33}	-0.09163	0.0250	-3.66	0.0009
β_{41}	-5.58806	0.3797	-14.72	<0.0001
β_{42}	2.217087	0.1117	19.85	<0.0001
β_{43}	-0.07627	0.0100	-3.82	0.0006

The parameter estimates in Tables 5 and 6 had lower standard errors compared to standard errors of the estimates of same parameters obtained when the component equations and the total tree biomass equation were fitted separately. This agreed with Paressol's (2001) observation that fitting tree and tree component biomass equations by NSUR results in efficient parameter estimates. The fit statistics for the equations, based on the parameter estimates in Table 6, are shown in Table 7. The fit index values show that the equations provide a good fit to the data. The fit index values were lower for branch and foliage equations, an indicator that branch and foliage biomass were associated with more unexplained variability than bole and whole tree biomass. Plots of residuals for the corresponding equations are shown in Appendix IV. The plots indicate that the models may not violate the constant error variance assumption.

Table 7 Fit statistics for the dbh only biomass equations fitted in the system of equations (14) without parameter β_{22}

Tree Part	Equation	Fit Index	RMSE
Bole Wood	$Y = \exp^{(\beta_{11}+\beta_{12}X_1)}(DBH)^{\beta_{13}}$	0.987	18.49
Tree Bole	$Y = \exp^{\beta_{21}}(DBH)^{\beta_{23}}$	0.986	20.21
Branches	$Y = \exp^{\beta_{31}}(DBH)^{[\beta_{32}+\beta_{33}X_1]}$	0.943	7.13
Foliage	$Y = \exp^{\beta_{41}}(DBH)^{[\beta_{42}+\beta_{43}X_1]}$	0.921	0.99
Whole Tree	$Y = \exp^{\beta_{21}}(DBH)^{\beta_{23}} + \exp^{\beta_{31}}(DBH)^{[\beta_{32}+\beta_{33}X_1]} +$ $\exp^{\beta_{41}}(DBH)^{[\beta_{42}+\beta_{43}X_1]}$	0.986	26.31

where:

Y is the tree component biomass in kilograms

β_{11} to β_{43} are parameters

X_1 is a dummy variable with value 1 for unthinned stand and zero for thinned stands

The parameter estimates for the equations utilizing dbh, height and/or crown width as predictor variables, fitted in the system of equations (17), are shown in Table 8. All the parameters, except β_{24}, were significant at $p \leq 0.05$.

Table 8 Estimates and significance statistics for the parameters of biomass equations fitted in the system of equations (17)

Parameter	Estimate	Standard Error	t-value	p-value
β_{11}	-3.47996	0.4788	-7.27	<0.0001
β_{12}	1.984397	0.0608	32.63	<0.0001
β_{13}	0.814912	0.1949	4.18	0.0002
β_{14}	-0.02202	0.00758	-2.91	0.0066
β_{21}	-3.60433	0.4674	-7.71	<0.0001
β_{22}	1.956015	0.0593	32.97	<0.0001
β_{23}	0.913537	0.1898	4.81	<0.0001
β_{24}	-0.01347	0.00723	-1.86	0.0718
β_{31}	-6.94109	0.3915	-17.73	<0.0001
β_{32}	2.636473	0.1758	15.00	<0.0001
β_{33}	0.879174	0.1360	6.47	<0.0001
β_{41}	-4.73214	0.5450	-8.68	<0.0001
β_{42}	1.707013	0.2270	7.52	<0.0001
β_{43}	0.447436	0.1566	2.86	0.0074

The insignificance of the parameter β_{24} suggested that the dummy variable $X_1$was not important in the tree bole equation. However, the significance was close to the arbitrary cutoff of 0.05 ($p = 0.0718$) hence the parameter was left in the equation. The corresponding biomass estimates were found to be additive. The fit statistics for the equations are shown in Table 9. The fit index values show that the equations provide a good fit to the data. As in the dbh-only equations, the fit index values were lower for branch and foliage equations. Plots of residuals for these equations are shown in Appendix V. These plots indicate that the models may not violate the constant error variance assumption.

Comparing the fit index and RMSE values in Tables 7 and 9, the equations with tree height and/or crown width in addition to dbh, as dendrometric predictor variables, have better fit statistics with the exception of the foliage biomass equation. It appears that the dummy variable X_1 captures the variation in foliage biomass better than crown width; hence the better fit statistics for the dbh-only equation. The fit index statistics, however, do not appear to differ, hence the two types of models essentially have the same predictive ability.

A comparison of the two types of equations for bole wood, tree bole, and whole tree prediction using the F-test as explained by Motulsky and Christopoulos (2004). This test did not indicate differences between the predictive abilities of the two types of equations. The comparison is shown in Appendix VI. The dbh-only equation could be used with results as good as those that could be obtained using equations with dbh, tree height, and/or crown width. This may be attributed to the fact that the data used to fit the equations were from the some geographic area. The variable dbh tends to account for

Table 9 Fit statistics for the biomass equations fitted in the system of equations (17)

Tree Part	Equation	Fit Index	RMSE
Bole Wood	$Y = \exp^{\beta_{11}} (DBH)^{\beta_{12}} H^{(\beta_{13}+\beta_{14}X_1)}$	0.990	16.19
Tree Bole	$Y = \exp^{\beta_{21}} (DBH)^{\beta_{22}} H^{(\beta_{23}+\beta_{24}X_1)}$	0.988	18.95
Branches	$Y = \exp^{\beta_{31}} (DBH)^{\beta_{32}} (CW)^{\beta_{33}}$	0.956	6.09
Foliage	$Y = \exp^{\beta_{41}} (DBH)^{\beta_{42}} (CW)^{\beta_{43}}$	0.904	1.07
Whole Tree	$Y = \exp^{\beta_{21}} (DBH)^{\beta_{22}} H^{(\beta_{23}+\beta_{24}X_1)} +$ $\exp^{\beta_{31}} (DBH)^{\beta_{32}} (CW)^{\beta_{33}} + \exp^{\beta_{41}} (DBH)^{\beta_{42}} (CW)^{\beta_{43}}$	0.988	23.75

where:

Y is the tree component biomass in kilograms

β_{11} to β_{43} are parameters

X_1 is a dummy variable with value 1 for unthinned stand and zero for thinned stands

most of the variability in stem content as there is very little variation in height of trees of the same age and species growing on the same site index. There is, however, a possibility that this observation is not due to the local nature of the data but the general trend of biomass equations. Several authors (Freedman et al. 1982, Campbell et al. 1985, and Harding and Grigal 1985) have observed that the addition of height as a predictor variable, to a biomass equation already containing dbh, does not result in substantial increase in the fit index and reduction in RMSE. Validating the equations using an independent data set from an area with a different site index can help evaluate the validity of this observation.

Conclusions and Recommendations

Tree and tree component biomass equations based on dbh alone and those based on dbh, tree height, and/or crown width were successfully fitted, by NSUR, for naturally regenerated shortleaf pine in southeast Oklahoma. Stand density seemed to have no effect on the exponents in the equations for the thinned treatment stands (as a result of the dummy variable X_1 having a value of zero for these stands) hence the same biomass equation can be used in stands of densities 90 to 115 percent of full stocking (stocking level at the time of data collection). For the unthinned stands (>120 percent of full stocking), an equation with some of the exponents different from those in thinned stands equations would be required (as a result of the dummy variable X_1 having a value of 1 for these stands). The presence of the variable crown width for branch and foliage equations, however, eliminated the need for a dummy variable for stand density in these equations. This suggests that crown width is a suitable quantitative variable for stand density. Its effective use may however be hampered by the fact that it is difficult to obtain accurate measurements of this variable under forest conditions.

The dbh range for the application of the equations should be limited to 7 to 40 cm, the dbh range of the trees that were used to fit the equations. The foliage biomass equations provide an estimate of the foliage that will be expected to fall off the trees during the fall season. The data for the study were collected during winter and the foliage that was on the trees was that which according to Kinerson et al. (1974) and Dougherty et al. (1995), was foliage set the previous growing season and expected to fall during the following fall season.

A clear advantage of equations with dbh, tree height, and/or crown width, over dbh-only equations, did not seem to exist. Dbh-only equations can therefore be used with predictions as good as those from the dbh plus tree height and/or crown width equations. Equations with dbh only as the dendrometric predictor would be the best for use by field foresters. These equations are easier to use as they do not require measurement of tree height and tree crown width, whose measurement is not easy under forest conditions. For research purposes, the equations with dbh, tree height, and/or crown width would be appropriate. The slightly better fit statistics of these equations can help provide extra information that researchers may desire.

Model validation on a data set independent of that used to fit the model parameters was not done. This was due to unavailability of an independent model validation data set. Strictly speaking, this could limit the use of the equations to shortleaf pine within the area from where the data for the study were collected. However, biomass equations have been observed to be versatile. West (2004) reported that a biomass function developed by Freedman (1984) for trees in Nova Scotia, Canada was applied by Specht and West (2003) to Eucalyptus and other trees in New South Wales, Australia with as much precision as was obtained by an equation developed for the Australian trees. The biomass equations fitted for shortleaf pine, therefore, have potential to be used successfully on naturally regenerated shortleaf pine growing in other areas. Additional validation may be done using data from similar biomass studies on shortleaf pine where available.

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Appendices

Appendix I. Biomass estimates and tree dimension data for each of the sampled trees

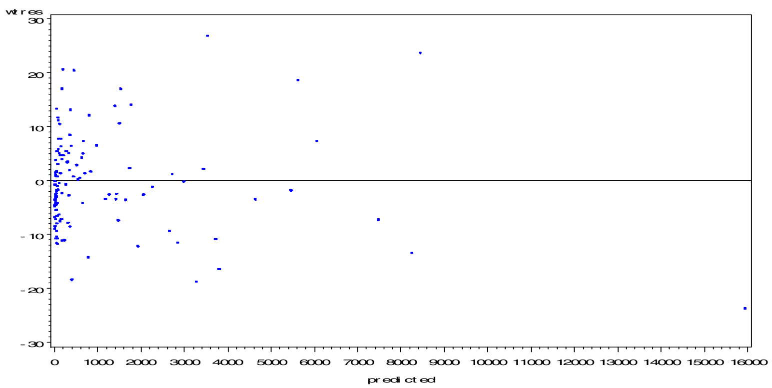
PLOT	TREE NUMBER	DBH (cm)	TOTAL HEIGHT (m)	CROWN HEIGHT (m)	CROWN LENGTH (m)	CROWN WIDTH (m)	BOLEWOOD BIOMASS (kg)	BOLE BARK BIOMASS (kg)	TOTAL BOLE BIOMASS (kg)	BRANCH BIOMASS (kg)	FOLIAGE BIOMASS (kg)	TOTAL TREE BIOMASS (kg)	TREATMENT
D	7	33.6	21.3	12.0	9.3	8.4	406.1	34.8	440.9	84.8	9.3	534.9	50FS
D	1	11.6	13.6	10.8	2.8	3.1	29.1	2.8	31.9	0.9	0.4	33.2	50FS
D	36	27.1	20.0	12.2	7.9	6.4	267.4	34.1	301.5	37.0	5.1	343.6	50FS
D	21	22.7	20.6	13.4	7.3	4.3	180.1	14.7	194.8	12.1	3.0	209.9	50FS
E	20	23.9	22.4	16.0	6.4	4.1	197.9	15.7	213.6	13.5	3.4	230.5	50FS
E	21	20.4	22.1	16.1	6.0	3.2	133.3	16.4	149.7	10.5	2.9	163.1	50FS
E	4	18.8	21.7	15.0	6.8	2.4	144.4	10.4	154.8	6.0	2.6	163.4	50FS
E	45	33.1	24.6	14.5	10.1	7.1	418.5	32.2	450.7	66.3	10.2	527.2	50FS
W	25	27.4	22.2	14.7	7.6	6.5	257.6	30.4	288.0	25.5	6.0	319.5	50FS
W	12	40.4	23.3	15.0	8.2	9.7	609.4	54.8	664.2	107.0	11.2	782.4	50FS
W	29	29.9	22.8	15.9	6.8	5.6	317.7	27.9	345.6	30.4	6.8	382.7	50FS
W	7	13.6	18.5	12.4	6.1	2.8	68.1	5.4	73.5	0.8	0.7	75.0	50FS
D	47	14.6	17.7	14.8	2.9	1.6	56.5	5.6	62.1	1.1	0.4	63.7	CTRL
D	170	23.7	21.8	16.2	5.6	3.4	190.5	20.0	210.5	12.8	2.7	226.0	CTRL
D	190	29.8	22.2	16.7	5.5	3.5	273.0	30.0	303.0	19.5	5.2	327.7	CTRL
D	192	7.3	8.2	6.6	1.6	1.7	8.2	1.1	9.3	0.7	0.6	10.6	CTRL
E	43	18.8	20.4	15.2	5.3	3.6	103.9	14.3	118.3	5.3	1.9	125.5	70FS
E	47	34.7	22.8	16.1	6.7	8.4	460.9	51.0	511.9	77.2	11.1	600.3	70FS
E	26	21.9	21.3	15.7	5.6	4.4	201.4	15.5	216.9	17.0	4.6	238.5	70FS
E	32	30.1	22.4	14.6	7.8	7.0	380.0	30.2	410.1	56.7	8.9	475.7	70FS
W	54	13.5	18.7	14.3	4.4	2.9	70.3	5.1	75.4	2.3	1.0	78.7	70FS
W	48	21.0	23.1	16.6	6.5	3.8	175.7	20.4	196.1	8.2	3.6	208.0	70FS
W	52	38.2	24.5	15.0	9.5	8.3	576.6	43.1	619.7	90.9	10.9	721.5	70FS
W	14	27.3	21.9	12.9	9.0	5.8	283.5	22.5	306.0	35.5	7.9	349.3	70FS
D	56	19.1	19.8	13.1	6.7	5.9	122.9	11.9	134.8	9.9	3.0	147.6	70FS

Appendix I (Continued)

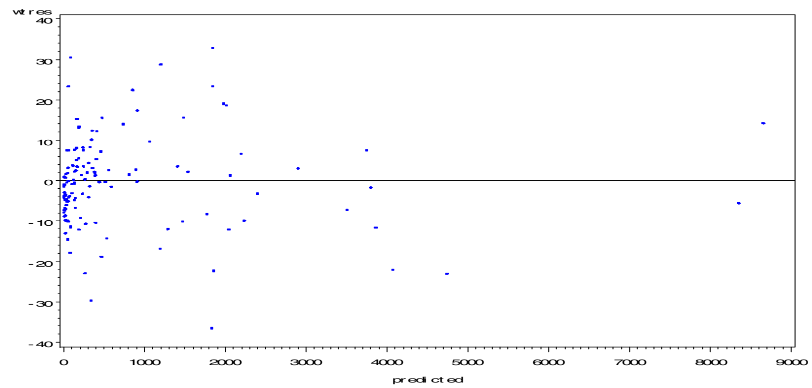
PLOT	TREE NUMBER	DBH (cm)	TOTAL HEIGHT (m)	CROWN HEIGHT (m)	CROWN LENGTH (m)	CROWN WIDTH (m)	BOLEWOOD BIOMASS (kg)	BOLE BARK BIOMASS (kg)	TOTAL BOLE BIOMASS (kg)	BRANCH BIOMASS (kg)	FOLIAGE BIOMASS (kg)	TOTAL TREE BIOMASS (kg)	TREATMENT
D	52	26.5	21.3	13.4	7.9	7.6	244.7	21.6	266.3	30.2	6.6	303.0	70FS
D	65	31.2	22.0	13.6	8.4	6.8	351.3	30.5	381.8	50.4	8.9	441.1	70FS
D	66	28.7	21.7	15.0	6.7	5.2	289.2	23.6	312.8	28.0	5.9	346.7	70FS
E	86	35.1	23.1	14.7	8.4	6.9	421.7	35.7	457.4	57.0	6.0	520.4	CTRL
E	85	13.3	18.2	14.8	3.4	1.7	43.6	4.4	48.1	0.3	0.1	48.5	CTRL
E	82	18.7	22.0	17.0	5.0	2.1	133.3	12.4	145.7	4.8	1.8	152.3	CTRL
E	84	26.3	22.2	15.4	6.8	4.4	254.9	24.1	279.0	15.6	4.0	298.6	CTRL
W	66	19.6	21.0	15.1	5.9	2.2	108.4	11.1	119.5	5.4	2.0	126.9	CTRL
W	128	9.4	14.1	12.7	1.4	2.0	21.5	2.6	24.1	0.8	0.3	25.3	CTRL
W	177	33.5	24.2	14.1	10.1	7.0	414.1	40.6	454.6	49.0	7.9	511.6	CTRL
W	176	28.1	24.7	16.1	8.6	3.9	289.4	78.4	367.8	19.8	5.1	392.8	CTRL

TREATMENTS:
50FS – Thinned to 50 percent of full stocking
70FS – Thinned to 70 percent of full stocking
CTRL – Unthinned Controls

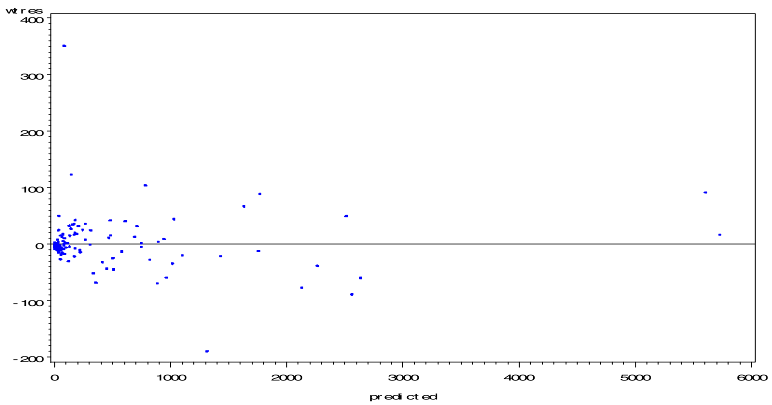
Appendix II. Residual plots for single branch foliage and branch (without foliage) biomass equations



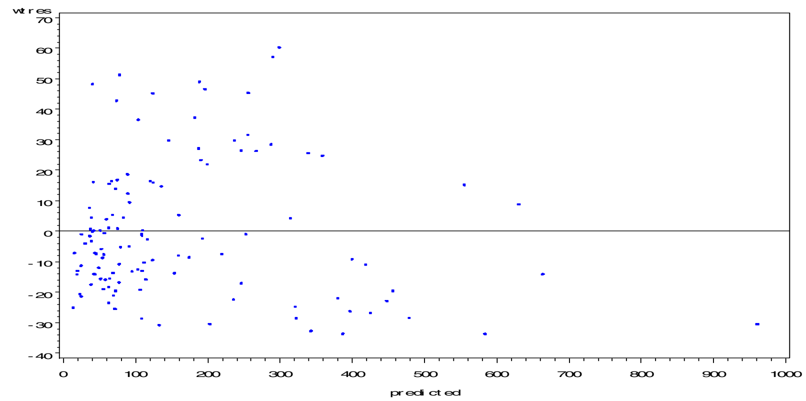
Residual plot for the thinned to 50% of full stocking branch biomass equation



Residual plot for the thinned to 70% of full stocking branch biomass equation

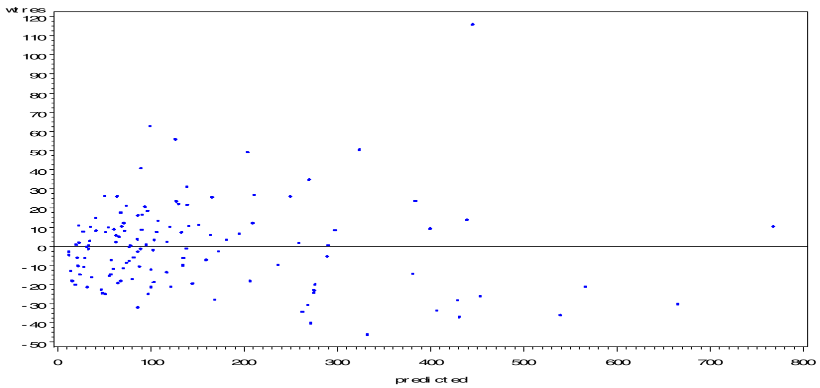


Residual plot for the unthinned stands branch biomass equation

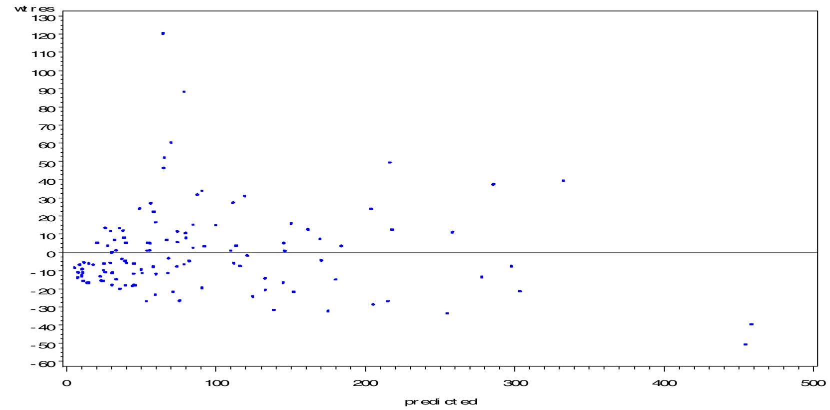


Residual plot for the thinned to 50% of full stocking foliage biomass equation

Appendix II. (Continued)



Residual plot for the thinned to 70% of full stocking foliage biomass equation



Residual plot for the unthinned stands foliage biomass equation

Appendix III: Estimates, standard errors, and significance statistics for the parameters of the single branch foliage and branch (without foliage) biomass equations

1. Equation $w = \beta_1 d^{\beta_2} \varepsilon$ for dry weight of branches (without foliage) in thinned to 50% full stocking treatment.

Parameter	Estimate	Standard Error	95% Confidence Interval
β_1	17.3102	1.0566	(15.2176, 19.4029)
β_2	2.8464	0.0396	(2.7680, 2.9247)

2. Equation $w = \beta_1 d^{\beta_2} S^{\beta_3} \varepsilon$ for dry weight of branches (without foliage) in thinned to 70% full stocking treatment.

Parameter	Estimate	Standard Error	95% Confidence Interval
β_1	16.4410	1.0887	(14.2863, 18.5958)
β_2	3.0065	0.0534	(2.9008, 3.1122)
β_3	0.3650	0.1334	(0.1010, 0.6289)

3. Equation $w = \beta_1 d^{\beta_2} \varepsilon$ for dry weight of branches (without foliage) in unthinned treatment.

Parameter	Estimate	Standard Error	95% Confidence Interval
β_1	17.9146	2.1226	(13.7120, 22.1172)
β_2	2.8150	0.0701	(2.6762, 2.9538)

Appendix III (Continued)

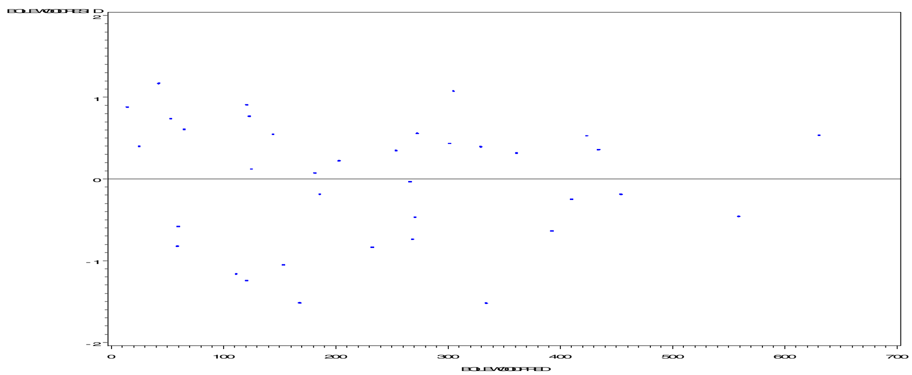
4. Equation $w = \beta_1 d^{\beta_2} R^{\beta_3} \varepsilon$ for dry weight of foliage in thinned to 50% full stocking treatment.

Parameter	Estimate	Standard Error	95% Confidence Interval
β_1	29.9575	2.9268	(24.1610, 35.7540)
β_2	1.6886	0.1289	(1.4333, 1.9440)
β_3	-0.3149	0.1003	(-0.5136, -0.1161)

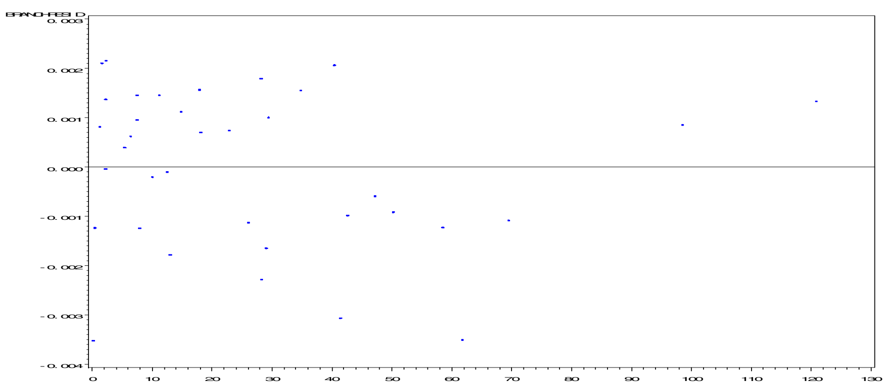
5. Equation $w = \beta_1 d^{\beta_2} R^{\beta_3} \varepsilon$ for dry weight of foliage in thinned to 70% full stocking treatment

Parameter	Estimate	Standard Error	95% Confidence Interval
β_1	25.4143	2.7367	(19.9981, 30.8306)
β_2	2.0003	0.1436	(1.7160, 2.2846)
β_3	-0.4452	0.0980	(-0.6391, -0.2513)

Appendix IV: Residuals for the equations with dbh as the only dendrometric predictor variable, fitted in the system of equations (14), without the parameter β_{22}

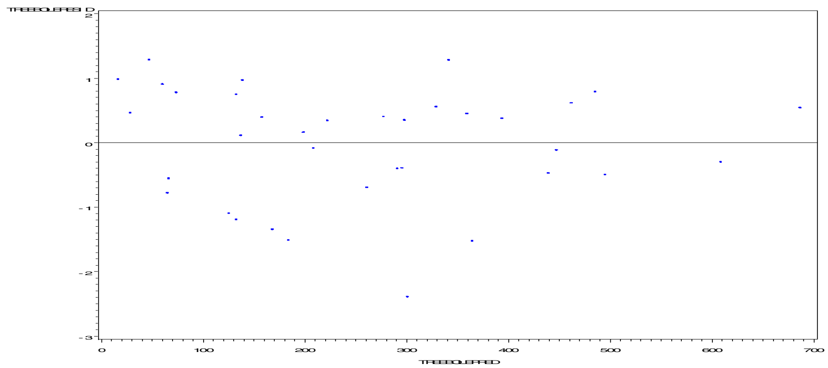


Residual plot for tree bole wood biomass equation

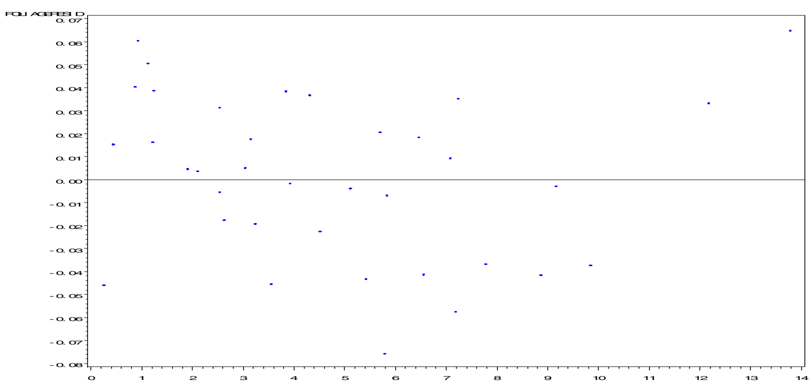


Residual plot for branch biomass equation

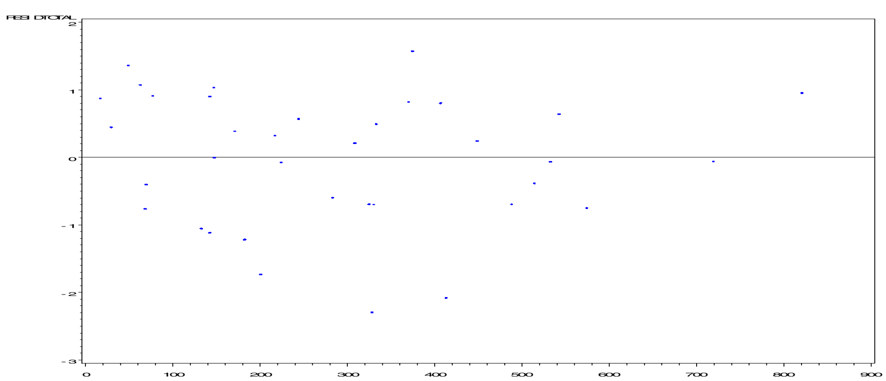
Appendix IV (Continued)



Residual plot for tree bole biomass equation

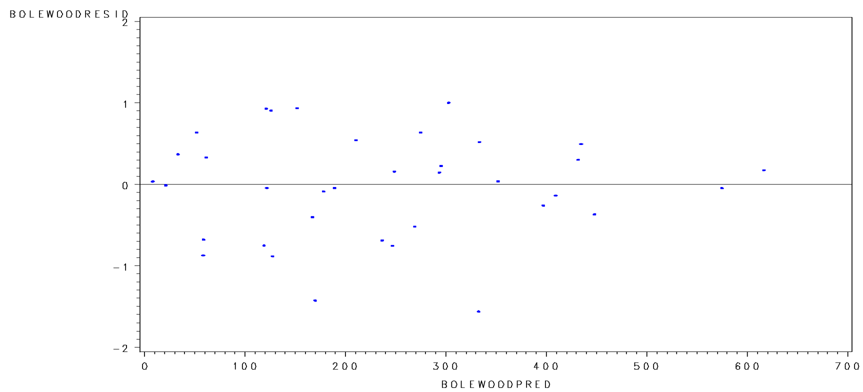


Residual plot for foliage biomass equation

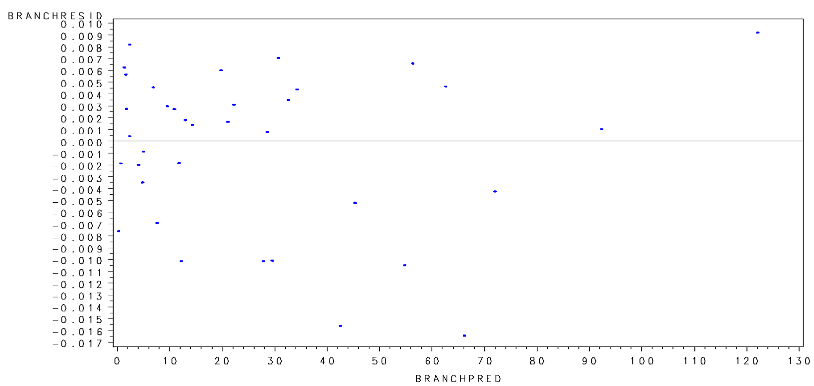


Residual plot for the total tree biomass equation

Appendix V. Residuals for the equations with dbh, height and/or crown width as dendrometric predictor variables, fitted in the system of equations (17)

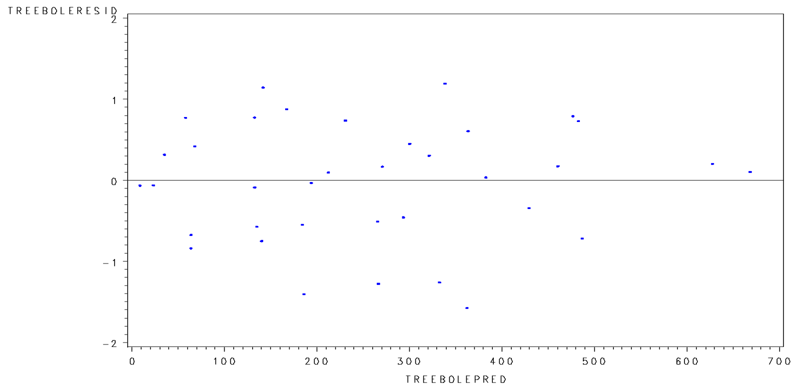


Residual plot for tree bole wood biomass equation

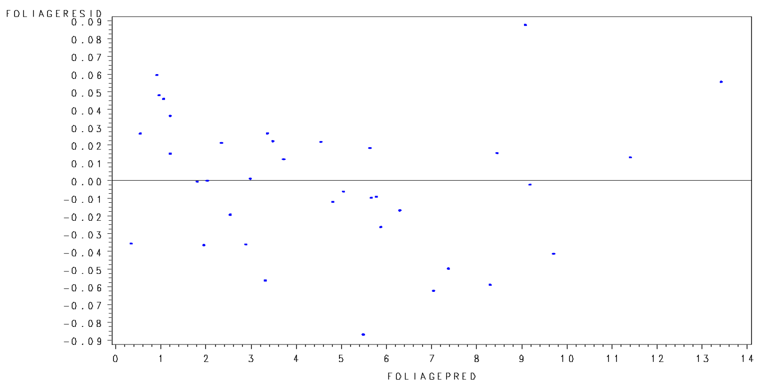


Residual plot for branch biomass equation

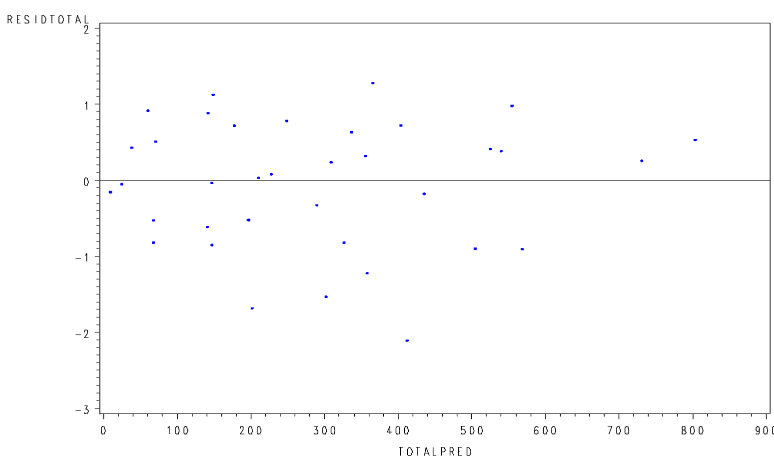
Appendix V (Continued)



Residual plot for tree bole biomass equation



Residual plot for foliage biomass equation



Residual plot for the total tree biomass equation

Appendix VI. Comparing the fits of two equations using F test

According to Motulsky and Christopoulos (2004), this may be done using the F ratio as follows:

$$F = \frac{(SS1 - SS2)/(DF1 - DF2)}{SS2/DF2}$$

where:

$SS1$ are the regression sums of squares for the equation with more parameters

$SS2$ are the regression sums of squares for the equation with fewer parameters

$DF1$ are the model degrees of freedom for the equation with more parameters

$DF2$ are the model degrees of freedom for the equation with fewer parameters

Comparing Bole Wood Equations

$$F = \frac{(831114.6672 - 828128.1745)/(4-3)}{828128.1745/3} = 0.0108$$

$F_{0.05\ df=1,3} = 10.13$

Conclusion: The fits of the two equations are not significantly different ($\alpha = 0.05$, $F_{df=1,3} = 0.0108$, p-value = 0.92379)

Comparing Tree Bole Equations

$$F = \frac{(979388.7877 - 975162.0981)/(4-2)}{975162.0981/2} = 0.00433$$

$F_{0.05\ df=2,2} = 19.00$

Conclusion: The fits of the two equations are not significantly different ($\alpha = 0.05$, $F_{df=2,2} = 0.00433$, p-value = 0.99569)

Comparing Whole Tree Equations

$$F = \frac{(1371514.657 - 1367134.474)/(10-8)}{1367134.474/8} = 0.0128$$

$F_{0.05\ df=2,8} = 4.46$

Conclusion: The fits of the two equations are not significantly different ($\alpha = 0.05$, $F_{df=2,8} = 0.0128$, p-value = 0.98730)

CHAPTER III

MANUSCRIPT II

EFFECT OF THINNING ON PARTITIONING OF ABOVEGROUND BIOMASS IN NATURALLY REGENERATED SHORTLEAF PINE (*PINUS ECHINATA* MILL.)

Abstract

The partitioning of biomass to different aboveground tree components was investigated in 46 – 53-year-old naturally regenerated shortleaf pine (*Pinus echinata* Mill.) stands that had received thinning treatments 16 years earlier (thinned to 50 percent full stocking, thinned to 70 percent full stocking, and unthinned control (>120 percent full stocking)). After 16 years, the unthinned controls had more total aboveground biomass, bole wood, bark, and foliage standing biomass per hectare but had less branch standing biomass than thinned stands. Comparing the amount of standing biomass partitioned to the aboveground components, no difference was observed in bole wood biomass and foliage biomass proportions among the three treatment levels. However, bark biomass proportion was significantly greater in unthinned controls with the proportion in the two thinning treatments being similar. The proportion in branches was significantly greater in the thinned to 50 percent treatment when compared to the proportion in the unthinned controls. These results suggest that thinning does not affect the partitioning of biomass to bole wood relative to other aboveground tree parts but affects partitioning to branches relative to bark, even after 16 years of post-thinning stand growth.

Introduction

Thinning is a forestry practice that allocates site resources to desirable trees such that growth, quality, and value of the residual stand are increased after thinning (Miller et al. 2001). According to Nyland (1986), foresters can also use thinning to control conditions of essential plant and animal habitats or to enhance other non-market values. Thinning generally increases bole diameter growth in the residual trees. Studies (Peterson et al. 1997; Juodvalkis et al. 2005) have shown that thinning also increases crown areas of the residual trees. Since growth of tree parts is as a result of accumulation of biomass within that component, thinning is likely to affect partitioning of biomass at least to the bole and the branches of trees in a stand.

Studies investigating the effect of silvicultural thinning in shortleaf pine have mostly concentrated on the effect on diameter growth and volume yield. Phipps (1973) reported significantly greater diameter growth, after 11 years of growth, for thinned 14- and 17-year-old shortleaf pine plantations in Indiana. Rogers (1983) used growing space requirements of shortleaf pine to develop stocking charts that could be used to thin shortleaf pine stands for increasing or maintaining diameter growth. Rogers and Sander (1985) reported the results of a 30-year study in a shortleaf pine stand in Missouri repeatedly thinned to constant stocking of 35, 50, 65, and 77 percent of full stocking since age 30 years. They found that stands repeatedly thinned to constant stocking eventually became understocked and lost volume. Wittwer et al. (1996) reported significantly greater diameter at breast height (dbh) growth in crop trees located in thinned plots, after 5 years of growth, for thinned 25- to 30-year-old natural shortleaf pine stands in the Ouachita Mountains of southeastern Oklahoma. However, there are no reported studies on the effect of thinning on crown sizes and on tree or tree component biomass in shortleaf pine. With the growing importance of biomass as a measure of forest resources, it is worthwhile understanding how thinning, a commonly used silvicultural tool in forestry, affects biomass partitioning in trees and stands as this would affect biomass yield of various tree components.

Biomass yield of various tree components is important to foresters and land owners managing stands for total tree harvesting, carbon sequestration, wildlife habitat, and for aesthetic purposes. The foresters or land owners managing stands for total tree harvesting need information on how thinning affects yield of not only the stem but total woody biomass. Those managing stands for carbon sequestration need information on how thinning may affect their carbon credits. Partitioning of biomass to woody parts relative to the non-woody parts is an important consideration when looking at the best management option to increase carbon sequestration. For stands being managed for wildlife habitat and aesthetic purposes through thinning and use of prescribed fire, e.g. the Forest Plan Amendment 1996 Management Area 22 (Guldin et al. 2004), information on biomass partitioning under different stand densities is helpful in deciding the thinning level that will result in the most manageable prescribed fire. Such thinning prescriptions could be based on fine fuel and coarse fuel loads of stands under different densities to maximize ecological benefits and reduce the risks. This information is particularly important for shortleaf pine, which is being managed in the Ozarks of Missouri and the Ouachita of Arkansas and Oklahoma for ecological restoration purposes (Manuscript I).

The objective of this study was to investigate the effect of thinning on the partitioning of biomass to bole wood, bole bark, branches, and foliage in even-aged naturally regenerated shortleaf pine. Specifically, 1) to quantify the biomass (in kg ha^{-1}) in bole wood, bole bark, branches, and foliage for shortleaf pine growing in experimental plots thinned to 50 percent of full stocking, thinned to 70 percent of full stocking, and unthinned controls (> 120 percent of full stocking); and 2) to compare the biomass in the different aboveground tree components among the three stocking densities.

Methods

Study Area

The study site was located in the Ouachita Mountains in Pushmataha County in southeast Oklahoma on industrial forest lands owned by Plum Creek Timber Company. The experimental plots were established in1990 to study the effect of thinning, done in stands already overstocked, on volume growth and yield of shortleaf pine (Wittwer et al. 1998). The details of the study area are given in Manuscript I.

Experimental Design and Treatment Design

The study was a randomized complete block design of three blocks. Each block contained three circular plots, each about 0.08 ha, which served as experimental units. Individual plots were several chains apart and each was surrounded by a 10.1 meter buffer strip. Interference on one of the original plots by a logger resulted in one of the experimental plots being reduced to 0.04 ha. Each plot in a block was randomly allocated to the two thinning treatments or was left to serve as an unthinned control. The treatment design for the experiment was one-way treatment design with three levels - thinned to 50 percent of full stocking (50FS), thinned to 70 percent of full stocking (70FS), and the unthinned control whose stocking was greater than 120 percent of full stocking (CONTROL). The shortleaf pine stocking guide developed by Rogers (1983) was used to guide the thinning to the required percent stocking. Thinning treatments were implemented using the low thinning method, removing trees from the lowest crown classes first, then progressing to trees in the higher crown classes as thinning intensity increased. Individual tree quality and spatial distribution of residual trees was also considered (Wittwer et al. 1996, 1998). The allocation of the plots in each block, to the various treatments, and some of the characteristics of the experimental plots, are shown in Table1.

Table 1. Allocation of experimental plots to the treatments and some characteristics of the plots in the year 2006

Plot	Treatment	Trees/ha	Dbh[4] (cm)	Basal Area (m^2/ha)
COX D1	50FS[1]	540	27.9	33
COX E1	50FS	630	26.4	35
COX W1	50FS	518	28.4	33
COX D3	70FS[2]	935	24.4	44
COX E2	70FS	740	25.1	37
COX W2	70FS	802	25.3	40
COX D2	CTRL[3]	1756	19.9	54
COX E3	CTRL	1148	22.4	45
COX W3	CTRL	1452	20.8	50

[1] Thinned to 50 percent of full stocking thinning treatment

[2] Thinned to 70 percent of full stocking thinning treatment

[3] Unthinned Controls

[4] Quadratic mean dbh

The letter D, E, or W in the plot label indicates the block in which the plot was found

Biomass Estimation

Tree and tree component biomass for each of the experimental plots was estimated in January and February of 2006 after sixteen years of growth since the time the thinning treatments were applied. Tree biomass equations (1), (2), (3), and (4), fitted as described in Manuscript I, were used to estimate component biomass for each tree in the experimental plot.

$$Y_{BOLEWOOD} = \exp^{-3.47996}(DBH)^{1.984397} H^{(0.814912 - 0.02202 X_1)} \tag{1}$$

$$Y_{TREEBOLE} = \exp^{-3.60433}(DBH)^{1.956015} H^{(0.913537 - 0.01347 X_1)} \tag{2}$$

$$Y_{BRANCHES} = \exp^{-6.94109}(DBH)^{2.636473}(CW)^{0.879174} \tag{3}$$

$$Y_{FOLIAGE} = \exp^{-4.73214}(DBH)^{1.707013}(CW)^{0.447436} \tag{4}$$

where:

the dependent variable in each of the equations is the tree component biomass

H is the height of the tree in meters

CW is the crown width of the tree in meters

X_1 is a dummy variable with value 1 for unthinned stand and zero for thinned stands

Equations (1)-(4) with fit indices 0.990, 0.988, 0.956 and 0.904 respectively were used to estimate bole wood, tree bole, branch, and foliage biomass. Bark biomass was obtained by subtracting the estimated bole wood biomass from the estimated tree bole biomass. Total tree biomass was obtained by summing the estimated tree bole, branch, and foliage biomass. The equations had been fitted by nonlinear seemingly unrelated regression method and were additive. Hence, no illogical estimates could result from the addition and subtraction operations. Plot biomass estimates were obtained by summing up the estimates for each tree in the plot and scaled to per hectare estimates. The per hectare plot biomass estimates are shown in Appendix I. The proportion of total plot biomass in the various tree components was calculated and is shown in Appendix II.

Statistical Analysis

The effect of the treatments was investigated by doing a mixed model analysis of variance, and multiple comparisons of the means, by the Restricted Maximum Likelihood (REML) approach using the MIXED procedure in SAS/STAT® software, Version 9.1.3 (SAS Institute Inc. 2000-2004). Multiple comparisons of the means was performed by the Tukey HSD adjustment. In all the comparisons, the hypothesis of equality of the treatment means was rejected if the probability for type I error was less or equal to 0.05 experiment-wise error rate.

Comparisons were made for the quadratic mean diameter and basal area per hectare (Table 1) the immediate post thinning mean basal areas (Table 4), the per acre biomass estimates for the trees and tree components (Appendix I), branch diameters and live crown ratio (Table 6), and the component biomass estimates as a proportion of the total plot biomass (Appendix II). The component proportions were transformed by the arcsine square root transformation method to ensure equal variance of the proportions among the treatments.

Results and Discussion

For current stand conditions, the control treatment had a significantly higher number of trees per hectare, smaller tree size, and higher basal area per hectare than the thinned treatments. Compared to the thinned to 50 percent of full stocking (50FS) treatment, the thinned to 70 percent of full stocking (70FS) treatment had more trees per hectare and a higher basal area per hectare but these differences were not statistically (p = 0.2733 for trees/ha and p = 0.1055 for basal area/ha). However, the 50FS treatment had trees that were significantly larger than those in the 70FS treatment (Table 2).

Table 2. Year 2006 mean number of trees/ha, basal area, and quadratic mean dbh for the stands under the different treatment levels

Trt	Stocking (%)	Trees/ha	S.E.	Dbh[1] (cm)	S.E. (cm)	BA[2] (m^2/ha)	S.E. (m^2/ha)
50FS	90	562 a	34	27.6 a	0.6	33.7 a	0.7
70FS	115	825 a	57	24.9 b	0.3	40.3 a	2.0
CONTROL (>120FS)	>120	1452 b	175	21.0 c	0.7	49.7 b	2.6

[1] Quadratic mean dbh

[2] Basal area

S.E. is the standard error of the mean in the preceding column

Means within the same column indicated by the same letter a, b, or c; are not significantly different at $p \leq 0.05$

Table 3 gives the changes in the number of trees/ha and the basal area of the stands during the 16-year experimental period. The greater basal area growth in stands under

Table 3 Changes in mean basal area (BA) and mean number of trees per ha (Trees/ha) for stands in different treatments during the period 1990 to 2006

Trt	50FS		70FS		CONTROL(>120FS)	
Stand Variable	BA (m^2/ha)	Trees/ha	BA (m^2/ha)	Trees/ha	BA (m^2/ha)	Trees/ha
2006	33.7	562	40.3	825	49.7	1452
1990	16.0	567	22.3	850	40.5	2287
Change	+17.7	-5	+18.0	-25	+9.2	-835

thinned treatments suggests that stand bole growth was greater for treatments that had a higher level of thinning intensity. Wittwer et al. (1996) found similar results, after five years of growth, in a similar experiment on the same species that was conducted at a site thirty-five miles to the southeast of the study site of this study. The insignificance of the difference in basal area per hectare of the 50 FS and the 70FS treatments ($p = 0.1055$) suggests that the basal areas for the two densities had started converging. Immediate post thinning differences in basal areas of the stands in the different treatments (Table 4) support this ($p = 0.0045$ for 50FS vs 70FS means). The basal area means for the 3 treatments were all significantly different at $p \leq 0.05$ at that time. The basal area of the 70FS treatment could also be converging towards that of the CONTROL treatment even though the basal areas of the two treatments are still significantly different after 16 years of growth (Table 2). Immediate post thinning basal area difference between 70FS treatment and the CONTROL treatment was much greater (18.2m^2/ha) than between

Table 4 Year 1990 mean basal areas (BA) for stands in different treatments

Treatment	50FS	70FS	CONTROL(>120FS)
BA (m^2/ha)	16.0 a	22.3 b	40.5 c
Standard Error	0.3	0.4	1.4

Means indicated by the same letter a, b, or c; are not significantly different at $p \leq 0.05$

70FS treatment and 50FS treatment (6.3 m^2/ha). More time would be required by the trees experiencing the higher competitive pressure in the 70FS treatment to bridge the 18.2 m^2/ha basal area gap than would be required by the trees experiencing a lower competitive pressure in 50FS treatment to bridge a 6.3 m^2/ha basal area gap. The difference of 9.4 m^2/ha between the 70FS treatment and the CONTROL treatment in year 2006 (Table 2) is much smaller compared to the difference of 18.2 m^2/ha in the year 1990 (Table 4). So, the basal area of the stands in the 70FS treatment is also converging towards that of the CONTROL treatment stands. Similar trends were observed by Pienaar et al. (1985) and Hasenauer et al. (1997) in slash pine (*Pinus elliottii*) and loblolly pine (*Pinus taeda*) respectively who found that basal area of thinned stands converges towards that of their unthinned counterparts. Biomass seems to follow the same trend at least for the tree bole (Table 5).

The mean total and tree component biomass for the various treatment levels are shown in Table 5. For total tree biomass, tree bole biomass, bark biomass, and foliage biomass, the amount of standing biomass was less for treatments that had a higher thinning intensity. These results are expected as some biomass was removed from the

Table 5. Year 2006 mean tree and tree component standing biomass for the various treatment levels

Trt	Mean biomass and standard error (SE) of the mean in kg/ha				
	Bole Wood	Bark	Branch	Foliage	Total aboveground
50FS[1]	157,380 a	14,320 a	17,927 a	3,165 a	192,792 a
	(SE: 6,765)	(SE: 1,285)	(SE: 1,310)	(SE: 55)	(SE: 7,094)
70FS[2]	184,497 ab	16,752 a	17,720 a	3,637 b	222,607 ab
	(SE: 8,322)	(SE: 670)	(SE: 509)	(SE: 181)	(SE: 9,662)
CTL[3]	210,231 b	25,554 b	14,929 a	3,922 b	254,636 b
	(SE: 8,922)	(SE: 955)	(SE: 484)	(SE: 143)	(SE: 4,597)

[1] Thinned to 50 percent of full stocking thinning treatment

[2] Thinned to 70 percent of full stocking thinning treatment

[3] Unthinned Controls

Means within the same column indicated by the same letter a or b are not significantly different at $p \leq 0.05$

stands when the thinning treatments were applied. The unthinned stands are expected to have more standing biomass until greater growth of residual trees in the thinned stands results in convergence of the standing biomass. The length of time needed to accomplish this is not documented for shortleaf pine biomass. However, some of the differences in per hectare biomass among the treatment levels were not statistically significant at $p \leq 0.05$. This suggests that the faster diameter growth in the more heavily thinned stands was starting to result in the biomass of the thinned stands converging to that of their unthinned counterparts.

For branch biomass, the amount of standing biomass was greater for treatments that had a higher the thinning intensity. However, the differences were however not statistically significant at $p \leq 0.05$. At $p \leq 0.1$, the thinned treatments (50FS and 70FS) had a significantly greater per hectare branch standing biomass than the unthinned ($p = 0.0767$ and 0.0939 respectively). The branch standing biomass in 50FS treatment was not significantly different from that in the 70FS treatment ($p = 0.9754$). Similar results were obtained by Bartelink (1998) who observed, in Douglass-fir (*Pseudotsuga menziesii* Mirb.) and American beech (*Fagus sylvatica* L.), that thinning resulted in increased biomass partitioning to branches. Baldwin et al. (2000) also observed a similar trend in 38-year-old loblolly pine (*Pinus taeda* L.) experimental plantations in Louisiana. They found that heavier thinning resulted in a larger number of branches, longer branches, and branches with wider diameters, which resulted in greater branch biomass for trees in the more heavily thinned experimental plots. Kramer and Kozlowski (1960) attributed larger branches in more heavily thinned stands to the need for larger branch size to support the increased amount of foliage produced by lower stand densities. Cannell (1989) reported that more biomass is partitioned to stems at the expense of branches under conditions of increased inter-tree competition while Bartelink (1996, 1997) observed that suppressed trees invest less dry matter in crowns. The study by Naidu et al. (1998), on loblolly pine, also showed that suppressed trees allocate less biomass to branches than dominant trees of the same diameter. Therefore, it is highly probable that standing branch biomass in the unthinned treatment is actually lower than in the thinned treatments. The smaller average branch basal diameters and smaller live crown ratios for trees in the unthinned treatment (Table 6) tend to support this.

A larger number of suppressed trees, each investing less dry matter in crowns, and greater inter-tree competition, in the unthinned stands and the development of more and larger branches, to support more foliage in the thinned stands; could be the cause of the differences in standing branch biomass among the treatment levels. A comparison of the branch biomass by dbh classes, by crown position, and by an interaction of dbh class and crown position for trees in the different treatment levels could help explain the exact cause of differences and assess the contribution of the various stand conditions, related to thinning, to biomass partitioning between branches and stems.

Table 6. Year 2006 mean quadratic mean branch basal diameter (QMBBD) and live crown ratio (LCR) for the various treatment levels

	Mean and standard error (SE) of the mean			
Trt	QMBBD (cm)	SE for QMBBD (cm)	LCR (%)	SE for LCR (%)
50FS[1]	3.6 a	0.2	32 a	1.2
70FS[2]	3.2 ab	0.1	28 b	1.7
CTL[3]	2.6 b	0.2	27 b	1.2

[1] Thinned to 50 percent of full stocking thinning treatment

[2] Thinned to 70 percent of full stocking thinning treatment

[3] Unthinned Controls

Means within the same column indicated by the same letter a or b are not significantly different at $p \leq 0.05$

Despite having different amounts of standing bole wood biomass per hectare, the bole wood biomass as a proportion of the total aboveground biomass did not differ among the treatment levels. Standing foliage biomass as a proportion of total aboveground biomass also did not differ among the treatment levels (Table 7). This shows that stand level partitioning of biomass to bole wood and to foliage, relative to the total aboveground biomass, was not altered by thinning. Thinned stands (50 FS and 70 FS) partitioned a significantly smaller proportion of total biomass to bark and a significantly higher proportion of total biomass to branches than unthinned stands (Table 7). Thinning therefore affected stand level partitioning of biomass to bark and branches. The larger average size of branches and the bigger live crown ratios for trees in thinned stands (Table 6) suggest that the trend could be the same at tree level. The larger number of small trees in unthinned stands (Table 2) could be the cause of the greater stand level biomass partitioning to bark. A larger number of small sized trees have a larger surface area to volume ratio which requires more bark compared to the smaller number of larger trees in the thinned stands.

Table 7. Year 2006 mean proportion of component standing biomass for the various treatment levels

Trt	Mean proportion and standard error (SE) of the mean in percentage (%)			
	Bole Wood	Bark	Branch	Foliage
50FS[1]	81.6 a	7.4 a	9.4 a	1.6 a
	(SE: 0.65)	(SE: 0.39)	(SE: 0.91)	(SE: 0.08)
70FS[2]	82.9 a	7.5 a	7.9 ab	1.6 a
	(SE: 0.15)	(SE: 0.05)	(SE: 0.22)	(SE: 0.02)
CTL[3]	82.5 a	10.1 b	5.9 b	1.5 a
	(SE: 0.18)	(SE: 0.10)	(SE: 0.15)	(SE: 0.018)

[1] Thinned to 50 percent of full stocking thinning treatment

[2] Thinned to 70 percent of full stocking thinning treatment

[3] Unthinned Controls

Means within the same column indicated by the same letter a or b are not significantly different at $p \leq 0.05$

Conclusions and Recommendations

Total standing biomass of naturally regenerated shortleaf pine stands thinned to 50 percent stocking and 70 percent of full stocking at the age of 30 to 37 years requires more than 16 years to converge with that of their unthinned counterparts. The greater basal area growth and the lower mortality in thinned stands (Table 3) suggest that an increase in biomass yield of a stand is possible with thinning. An estimate of biomass removed during thinning would be required to assess the benefit of thinning as far as the increase in biomass yield concerned. The higher growth rate in the thinned stands, if maintained, could see the convergence of the biomass if the trees were grown for a sufficient length of time. However, the practice of growing the trees to over 70 years is not commonly followed in managed shortleaf pine stands because net growth rates decline rapidly (Lawson 1990). A study of the trend in biomass growth up to this age may help provide information on the benefit of thinning on biomass yield to those managing shortleaf pine for biomass production and do not grow their shortleaf pine beyond 70 years. But for shortleaf pine stands being managed for shortleaf pine-bluestem restoration, whose rotation is a minimum of 120 years (Thill et al. 2004), convergence of the biomass is possible. Regular thinning in these stands, after the initial thinning, will be necessary to avoid convergence that may introduce stand conditions unsuitable for the achievement of the restoration objectives. Initial thinning to a stocking of less than 50 percent of full stocking may be the most appropriate as stands thinned to 50 percent of full stocking or higher may become fully stocked or overstocked in 16 years (Table 2).

Thinning is beneficial to wildland fire management especially for the natural shortleaf pine stands being managed with fire for ecological restoration e.g. the Forest

Plan Amendment 1996 Management Area 22 (Guldin et al. 2004). Thinned stands may have less intense fires hence easier management of the prescribed fires when they are applied. The most heavily thinned stands (50FS) produce about 19 percent less in foliage biomass annually than unthinned stands (Table 5) hence less annual fine fuel input. They also have a slower crown recession rate than the unthinned stands (Table 7) and experience much lower mortality (Table 3), hence their rate of production of coarse fuels will be lower. However, if whole tree harvesting is not used during thinning, thinning may see a rise in the amount of fuels in the short term as logging slash is left in the stands, which may result in short term higher fire risks in thinned stands. Thinning may also result in increased fire risks if the trees harvested during thinning are not removed from the stands.

Thinning may be beneficial to carbon sequestration especially if the trees removed during thinning are used in long half-life products such as furniture. The lower crown recession rates (Table 7) combined with lower mortality (Table 3) for trees in thinned stands help keep less biomass on the forest floor where decomposition would release the sequestrated carbon. The increased branch production in thinned stands increases the amount of woody biomass in the stands hence increased carbon sequestration.

Thinning causes changes in biomass partitioning between the crown and the tree bole at the stand level. The changes involve only the bark and the branches with a smaller proportion of total biomass partitioned to bark under conditions of more intense thinning. If this trend is the same at tree level, then higher diameter growth of individual trees that results from thinning is not due to increased partitioning of biomass to the bole but due to increased total biomass production at tree level. A study of the effect of thinning on biomass partitioning by tree diameter classes and by tree crown classes should give an insight of the trend at tree level.

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Appendices

Appendix I: Per hectare estimates of tree and tree component biomass in the experimental plots

Plot	Trt	Biomass (kg/ha)					
		Bole Wood	Bark	Tree Bole	Branches	Foliage	Total
COX D1	50FS[1]	147,338	12,346	159,684	18,224	3,167	181,075
COX E1	50FS	170,255	16,733	186,988	15,524	3,069	205,581
COX W1	50FS	154,547	13,881	168,428	20,033	3,259	191,720
COX D3	70FS[2]	197,538	17,663	215,201	18,390	3,968	237,559
COX E2	70FS	169,018	15,445	184,463	16,721	3,345	204,529
COX W2	70FS	186,936	17,149	204,085	18,049	3,599	225,733
COX D2	CTRL[3]	224,079	26,710	250,789	15,899	4,188	270,876
COX E3	CTRL	193,560	23,657	217,217	14,429	3,696	235,342
COX W3	CTRL	213,053	26,294	239,347	14,460	3,884	257,691

[1] Thinned to 50 percent of full stocking thinning treatment
[2] Thinned to 70 percent of full stocking thinning treatment
[3] Unthinned Controls

Appendix II: Proportion of total plot biomass in each tree component

Plot	Trt	Proportion of total plot in the tree component (%)			
		Bole Wood	Bark	Branches	Foliage
COX D1	50FS[1]	81.37	6.82	10.06	1.75
COX E1	50FS	82.81	8.14	7.55	1.49
COX W1	50FS	80.61	7.24	10.45	1.70
COX D3	70FS[2]	83.15	7.44	7.44	1.67
COX E2	70FS	82.64	7.55	8.18	1.64
COX W2	70FS	82.81	7.60	8.00	1.59
COX D2	CTRL[3]	82.72	9.86	5.87	1.55
COX E3	CTRL	82.17	10.05	6.13	1.57
COX W3	CTRL	82.68	10.20	5.61	1.51

[1] Thinned to 50 percent of full stocking thinning treatment
[2] Thinned to 70 percent of full stocking thinning treatment
[3] Unthinned Controls

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The study focused on shortleaf pine in southeast Oklahoma with possible application to shortleaf pine in other regions of southern United States and to other southern pines. Tree biomass equations were fitted for the shortleaf pine by nonlinear regression techniques. The biomass equations were used to estimate tree and tree component biomass for trees in three different thinning treatment levels. Tree and tree component biomass in the different thinning treatment levels were then compared using ANOVA techniques.

Findings and Conclusions:

Thinning naturally regenerated shortleaf pine stands at the age of 30 to 37 years did not affect proportion of biomass partitioned to stem or foliage. Thinning, however, increased partitioning of biomass to branches and decreased partitioning to bole bark. These results indicate that thinning 1) does not alter the relationship between total aboveground growth and bole wood production, 2) increases branch production, an important consideration in whole-tree harvesting systems, carbon sequestration, and wood quality issues, and 3) does not alter the proportion of aboveground growth partitioned to leaf biomass, an important consideration for stand photosynthetic surface and fine fuels input.

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